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AERATION OF AIRCRAFT LUBRICATING OILS OVER A RANGE OF TEMPERATURE

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SUMMARY

Most of the studies of foam in the recorded literature refer to columns of foam produced by slow bubbling usually through a porous membrane of sintered glass or stone. This investigation of lubricating oil was conducted in a similar manner.

With aviation lubricating oil at 100° C, however, foam is not produced when bubbles of air are introduced through single open tubes or rapidly through membranes. Such bubbles are coarse, rise rapidly to the surface, and break at once. At lower temperatures, however, a column of foam is built up on aeronautical aviation oils.

Aeration problems in aircraft are therefore not mainly due to foam but to finely emulsified air that readily recirculates and is produced on each cycle by degassing of air, which is redissolved in oil, or by comminution of air in the gear pumps.

The existence of air emulsions in aeronautical lubricating oil at 100° C has been demonstrated visually and the amount of air in certain emulsions has been measured. The air emulsified in the oil is air in such fine bubbles that it remains at least temporarily dispersed throughout the liquid. The maximum bubble size recirculated in an air emulsion depends on the mechanical conditions at the point of air segregation. The composition of an air emulsion depends on the method by which it is produced. Emulsified air causes the aviation oil to appear light colored and opaque.

Three mechanical systems are described, which produced air emulsions in oil at 100° C. The greatest measured air content of any emulsion produced by these systems was about 15 percent by volume.

The effect of reduced pressure on the "tank" of a gear-pump circulating system, simulating an aircraft-engine lubricating system, was to increase the total volume of the air plus oil, as measured by the height of the oil level in the tank. Reducing the pressure on the tank rapidly produced small increases in volume, which partly disappeared again. The steady-state condition was reached very quickly. The emulsified air in the oil in the tank was not increased in quantity by reduced pressure but was much more finely dispersed. The appearance

of the oil changed greatly, principally because of the degassing of dissolved air in the tank. The effect of reduced pressure appears to be almost entirely confined to the cyclic effect of the dissolving of air and the degassing of oil.

An oil containing lubricating additives formed emulsions containing up to 15 percent air, whereas an unmodified oil formed emulsions containing up to 12 percent air. Use of either Dow Corning Fluid Type 200 (a polymerized silicone) or a mixture of glycerol with Aerosol OT (dioctyl sodium sulfosuccinate), in optimum concentration, reduced the emulsified aeration to a minimum of from 2 to 4 percent in both the unmodified oil and the oil containing lubricating additives. The 2 to 4 percent of air in the oils containing the foam and aeration inhibitors formed a stable emulsion that required many minutes to separate completely. The 10 to 12 percent emulsified air in the unmodified oil escaped completely in about 1 minute and 80 percent of it escaped in about 1/2 minute. The 10 to 15 percent air emulsified in the oil containing only lubricating additives was reduced to half in about 2 minutes.

Dow Corning Fluid Type 200 and the glycerol – Aerosol-OT mixture each completely eliminated surface froth on all oils tested.

INTRODUCTION

The definition of the aeration and frothing problem in aircraft lubricating systems is far from complete. Principal emphasis has heretofore been given to frothing, studying the segregated foam above a liquid, particularly as it is formed in laboratory experiments by bubbling a small stream of finely divided air through a long column of liquid.

There are many types of aeration, however, and even the volume of foam from a given liquid is found to depend on the mechanism employed, such as beating, circulating through a gear pump, and spraying (reference 1).

Observations of violently agitated circulating systems being continuously aerated show that there are phenomena which are not associated with slow bubbling in columns. In the following section, types of aeration and foaming described in this report are enumerated and a terminology to describe them is set up.

Previous work at this laboratory has shown that the time required for the collapse of a column of foam, formed from an unmodified lubricating oil at 100° C, is of the order of 3 minutes. The term "average lifetime of the gas in the foam" was used to describe the collapse of such a foam column when the aerating source was removed. This investigation was conducted to demonstrate that: (1) On rapidly circulated or agitated oil, no slowly rising head of foam forms that is comparable to

the head formed by finely divided air rising through a column of oil; (2) large bubbles in circulating or agitated oil do not form foams but escape harmlessly; (3) finely divided air persists as an air emulsion in circulating or agitated oil; and (4) the head of foam which may be produced in a circulating or agitated oil at 100° C is only a few centimeters in depth.

This investigation was conducted at Stanford University under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics.

NOMENCLATURE FOR AERATION AND FOAMING IN OIL

Air may be dispersed in oil in a variety of known ways as follows:

(1) Dissolved, in true molecular solution.

(2) In a froth or foam, which may be "wet" or "dry."

(3) In fine bubbles, which may vary in size from barely visible to 1 millimeter in diameter.

(4) In coarse bubbles, which segregate and break before they can be recirculated.

(5) In pipes, coarse bubbles may become essentially cylindrical with meniscuses at the ends, in which form they become "slugs."

(6) Air and oil may move together through pipes, each in a continuous phase, in channeled flow.

In considering the problem of aeration of lubricating oils in aircraft during flight, certain of the preceding types of air dispersion assume practical importance. The segregation of air from the oil is of paramount importance; air that separates readily in bubbles that break immediately is comparatively harmless, whereas air that takes a long time to separate or accumulates in operation causes trouble. Air that is drawn in by the scavenging pumps obviously cannot segregate from the oil until a free surface and a vent are provided, as in the oil tank. Air in categories (4), (5), and (6) in the preceding list tends to separate rapidly at a free surface in oil at 100° C, even though violent turbulence may oppose the separation. Air in categories (1), (2), and (3) separates comparatively slowly even at 100° C. Terms are subsequently defined which are measurable experimentally and relate the preceding rough classification to the practical problem.

Foam or froth.– A foam or a froth is an aggregation of air bubbles in oil in which the air is present in volume approximately equal to or greater than the oil. At the lower limit of the air-to-oil ratio in a foam, air bubbles are spheres, many of them undistorted by the presence of neighboring bubbles. The upper limit of the air-to-oil ratio depends on the minimum film thickness of the oil lamellae, the bubble size, and the amount of liquid contained at the edges and the corners of the slightly rounded dodecahedrons to which close-packed spheres deform as liquid is removed from between them. A foam containing close to 50 percent by volume of liquid is a "wet" foam. A foam containing less than 10 percent by volume of liquid is a "dry" foam.

This investigation has indicated that a dry foam of unmodified oil is found only in the top few millimeters of a column of foam that is draining quietly. Even a very gentle rate of bubbling air through the oil in a column keeps the foam wet to the top of the column, which may be 40 centimeters high. The head of foam sometimes observed on circulating oil was always wet with essentially spherical air bubbles. It may therefore be assumed that a dry foam cannot exist in the oil system of an airplane in flight.

Emulsified air.– Emulsified air is a dispersion of air in fine bubbles in the oil. The composition of an air emulsion will depend on the method by which it is produced. Since even fine bubbles escape rapidly from quiescent oil at 100° C, the continuous existence of an air emulsion depends on a steady state being reached in a dynamic system. The maximum bubble size recirculated in an air emulsion depends on the mechanical conditions at the point of air segregation. The experiments subsequently described herein indicated that it would be difficult to entrain bubbles of diameter greater than approximately 1 millimeter in a steady-state air emulsion in oil at 100° C. In a heterogeneous mixture of air bubbles of all sizes in oil moving through a pipe, the determination of which part is emulsified air can be made only by means of a separating device in which bubbles greater than a certain size will escape and those less than a certain size will be retained in the oil. The oil tank in an airplane in operation is such a device. An emulsion of air in oil is lighter in color than the oil itself and becomes translucent and bright yellow if as much as 10 percent by volume consists of emulsified air. The greater the amount of air emulsified and the finer its dispersion, the lighter and more nearly opaque the mixture becomes.

Total amount of aeration.– The total amount of aeration is the sum of the dissolved air, the emulsified air, the foam, and all other enclosed or entrained air for any given portion of the oil. If the total amount of aeration of an entire system is being considered, the volume of the oil plus air including foam would be measured or computed and compared with the volume of the oil and a correction added for dissolved air.

AERATION OF AIRCRAFT LUBRICATING OIL BY BUBBLING AIR INTO IT THROUGH SINGLE JETS

The stability of bubbles decreases greatly with size. Experiments were necessary to determine whether large bubbles could produce foam.

Apparatus and Procedure

The apparatus consisted of a 2-liter, glass, graduated cylinder set in a glass water bath kept at 93° C (200° F). The cylinder was filled with Aeroshell 120 to about the 1500-centimeter mark, whereas the water-bath level was at the 2000-centimeter mark. A tubing system was provided to blow air, which was dried by passage through a calcium-chloride tower, through a tube fitted with any selected jet into the oil. The air flow was measured by means of a manometer, which indicated the pressure drop across a calibrated capillary tube. The temperatures of the air going through this capillary and entering the bubbling tube were measured by thermometers inserted in the air stream.

Five glass jets about 2 inches long, of uniform bore over this length, were attached successively with rubber tubing to the end of the bubbling tube. The rate of air flow was varied from almost zero to a maximum of 77 centimeters per second. The height of the tubes in the oil was varied from near the surface of the oil to a depth of 12 inches below the surface.

The jets used were as follows:

(1) 0.5-centimeter (I.D.) heat-resistant capillary with single unconstricted opening

(2) 0.1-centimeter (I.D.) heat-resistant capillary with single unconstricted opening

(3) 0.05-centimeter (I.D.) heat-resistant capillary with single unconstricted opening

(4) Thermometer capillary with single unconstricted opening

(5) Coarse sintered glass bubbler with numerous pores

Results and Discussion

No significant amount of foam could be produced at 93° C by use of any of the jets with a single opening at any depth or at any air flow tried. A small fringe of foam, however, was observed in all instances, which consisted mostly of bubbles far less than 1 millimeter in diameter.

At high air flows, small bubbles coalesced before leaving the jet, thus producing large bubbles which always broke in a small fraction of a second after reaching the surface. A jet is considered to be "overloaded" when the bubbles coalesce near the jet instead of rising individually. With the thermometer capillary, bubbles of approximately 0.4-centimeter diameter reached the surface; even these bubbles broke in less than a second.

With the sintered glass bubbler, it was possible at 93° C to produce a column of foam about 3 inches high consisting of small bubbles. The pore size of the bubbler is believed to be of the same order of magnitude as the bore of the thermometer capillary. The bubbler also could be overloaded at comparatively high air flows, so that it delivered large bubbles and made a column of foam less than 3 inches high. In addition to the head of foam, the bubbler produced a considerable amount of emulsified air in the oil.

A pipe bubbler was constructed consisting of a 3/8-inch galvanized pipe closed with a coupling and plug, just above which 24 holes of 2-millimeter diameter were drilled in three rows around the pipe. No column of foam, other than the usual fringe patches, was produced although there were sufficient bubbles to cover the oil surface entirely. After bubbling a few minutes, the oil above the air holes contained emulsified air, which appeared opaque and formed a sharp line at the base of the bubbler. The appearance remained unchanged after bubbling for 1 hour. When the oil temperature was lowered to 28° C, the pipe bubbler produced a column of wet foam 4 inches high. Air was still channeling through the foam, however, an indication that not all the air being introduced produced foam; thus the rate of foam breakage was not equal to the rate of air input.

Small bubbles are apparently required to form foam at 93° C. Although enough large bubbles are supplied to maintain a complete layer on the oil surface, no foam head builds up. The conclusion is reached that small bubbles are much more stable than large bubbles and that bubbles greater than a certain size, of the order of 3-millimeter diameter, are incapable of producing a foam at 93° C.

AERATION OF AIRCRAFT LUBRICATING OIL IN RECYCLING SYSTEMS

Most of the information in this report was obtained using mechanical devices which circulated aircraft lubricating oil under aerating conditions. Two of these devices roughly simulated the oil circulating system of an aircraft engine.

Apparatus

Three devices were used to aerate the lubricating oil mechanically.

An electric kitchen mixer.- A conventional double-paddled electric kitchen mixer, complete with an accessory glass bowl with sides especially shaped to match the curve of the paddle blades was used. Results of the aeration of oils in the electric kitchen mixer are shown in table I.

A colloid mill.- The hopper of the compact, recirculating type of colloid mill used in this investigation (fig. 1) has a capacity of 2 liters. The machine is driven by a 1/4-horsepower motor with an unloaded rotor speed of 8000 rpm. The rotor acts as a centrifugal pump, sucking liquid from the hopper and through the rotor and driving it out through a two-way valve; thus the liquid is permitted to be drawn from the mill or recycled through a short, gooseneck pipe and returned to the top of the hopper in the center directly above the rotor intake.

A glass air jet was fitted inside the hopper, 1/4 inch above the rotor, through which any desired rate of air could be injected into the oil. The rate was measured by the pressure difference across a capillary in the air tube. The downward velocity of oil above the rotor was so great that all the air was carried through the mill and none bubbled back up through the oil in the hopper. A stick was sometimes placed under the pipe, which delivered the oil back into the hopper, diverted the stream smoothly against the side of the hopper, and prevented the aerated oil from plunging immediately into the rotor intake. Results of the aeration of Aeroshell 120 at 100° C in the colloid mill are shown in table II. The colloid mill disperses the air so finely, without chemical change to the oil, that total separation is very slow. The baffle, which prevents immediate recirculation of highly aerated oil, is an important factor in reducing the amount of finely emulsified air.

A gear-pump circulating system.- The gear pump circulates oil through 1/4-inch galvanized pipe from the bottom of a 2-liter "tank," through a short length of pipe heated by open flame burners, through the pump, and back to the tank. The maximum rated pump delivery was 1 gallon per 100 revolutions.

Two interchangeable containers were used for the tank. For experiments at atmospheric pressure, the tank consisted of a 2-liter heat-resistant glass beaker, bored to permit the passage of 1/4-inch pipe through the center of the bottom (fig. 2). The inside of the pipe was fitted with an elbow, so that the fluid was drawn off in a horizontal direction. The pipe was sealed into the bottom of the beaker with rubber gaskets held between iron washers. The return pipe from the pump was a vertical pipe directly above the center of the beaker. Pipes of different lengths could be inserted to cause the delivery to be impingent on the surface or submerged below it. This arrangement of delivery and drawing off of the fluid caused extreme turbulence inside the beaker.

For experiments at reduced pressure, the tank consisted of a 2-liter, heat-resistant-glass, conical filter flask, which was similarly bored and fitted through the center of the bottom (fig. 3). Rubber pressure tubing connected the side arm of the flask to a vacuum pump. The inlet pipe passed through a rubber stopper at the top of the flask, completing the seal and permitting the flask and circulating system to be evacuated. An absolute manometer was connected to the system. The vertical delivery pipe into the conical flask from the pump was either straight, to deliver downward, or fitted with an elbow, to deliver against the sloping wall of the conical flask. When the straight pipe was used for delivery into the flask, a thermometer was inserted through the stopper. With the elbow on the pipe, there was not room for the thermometer, so the temperature was measured at atmospheric pressure and the thermometer was removed to seal the system for evacuation.

The aeration sampling method was modified by introducing a capillary tube through the stopper in the conical flask, so that aerated oil could be drawn up and the air volume measured in a syringe pipette, even at reduced pressure. The intake into the capillary was horizontal with a bell on the end to draw in large bubbles but it was incapable of trapping any air. The volume of oil retained by the capillary was about 0.5 cubic centimeter.

Procedure

Beating method, electric kitchen mixer.- A 90-gram sample of oil was heated to approximately 100° C and poured into the bowl of the electric mixer, which had been preheated to about the same temperature in an oven. The bowl was set in place under the paddles of the electric mixer, and the whole machine was set in an oven at 100° C. The oil was beaten at the top speed of the mixer for 3 minutes. (Preliminary experiments showed no change after this time.) The mixer was stopped and the oil-air mixture poured as rapidly as possible from the bowl to the top mark of a 100-cubic-centimeter graduated cylinder, which had likewise been preheated to 100° C. The cylinder was immediately immersed in the water of a glass-walled thermostat maintained at 95° C. The pouring operation required slightly less than 30 seconds. Speed was essential as most of the air had escaped even in this time, as shown by the circulating-system experiments.

An approximation of the effect of temperature on the quantity of emulsified air was obtained by heating the sample of Aeroshell 120 to 100° C and permitting it to cool slowly to room temperature while it was beaten continuously in the electric-mixer bowl. The increase in air was noted by the change in color of the oil and the actual volume of air was estimated visually.

Colloid-mill method.- Warmed oil (200 cc at 60° to 80° C) was poured into the hopper of the colloid mill and the mill was run with the oil recirculating. The temperature rose to 100° C in about

5 minutes as a result of friction. Samples were drawn from the drain valve when the temperature was between 95° and 105° C into preheated 100-cubic-centimeter graduated cylinders, which were immersed in the glass-walled thermostat at 95° C, and the escape of the air was measured.

Gear-pump-circulating-system method.- In all the tests with the gear-pump circulating system, the general method of operation was the same. Warmed oil $\left(1\frac{1}{2}\text{ liters}\right)$ was poured into the tank and the pump was started. The burners were lighted under the return pipe to the pump and were adjusted to hold the temperature of the rapidly circulating oil at 100° ± 5° C.

Air injection was controlled by a tap on the low-pressure side of the gear pump. When the tap was closed, no aeration occurred except in the tank. When the tap was opened, air was drawn into the pump. The amount of air drawn in was adjusted to the maximum that did not visibly affect the oil flow rate. Exploratory experiments showed that a larger amount of air reduced the flow rate and caused the emulsified air to be more finely dispersed but did not increase the amount of emulsified air in the tank.

The two tanks have already been described: A 2-liter beaker for atmospheric-pressure experiments and a conical flask for reduced-pressure experiments (figs. 2 and 3, respectively). Two types of oil delivery, controlled by the arrangement of the delivery pipe, were used with each tank: Impingent and submerged with the beaker and vertical and horizontal with the flask.

The pump speed was set at 575 rpm in the first beaker experiments (table III) but was increased to 2300 rpm in subsequent tests when it was found that the higher speed favored greater aeration.

In the first series of atmospheric-pressure experiments (table III), aeration was measured by drawing oil and air from the tap near the high-pressure outlet of the gear pump into a 100-cubic-centimeter graduated cylinder. In the later series of experiments at atmospheric pressure (table IV), the churning oil in the reservoir was sampled by withdrawing 30 cubic centimeters of the air-oil mixture in a syringe pipette. Consequently there was no chance for emulsified air to escape before being measured. The volume of air was read directly on the pipette after separation took place. The opening of the syringe pipette had about a 3-millimeter internal diameter and therefore the hot oil and air could be drawn in rapidly. There were visible variations and fluctuations in the appearance of the air emulsion in various parts of the reservoir. Three samples were usually taken from what appeared to be representative locations in the reservoir.

In the experiments at reduced pressure (table V), aeration was measured by drawing the oil-air mixture into the syringe pipette through the capillary tube in the stopper of the conical flask, already described. A short rubber connection between the capillary tube and the end of the

pipette permitted the pipette to be dipped to discharge entrapped air bubbles. The volume of oil retained in the capillary was about 0.5 cubic centimeter or about 3 percent of the 20-cubic-centimeter sample drawn in these experiments. This error is less than the error of estimating the air volume. The sample was drawn at reduced pressure and the air volume was read without disconnecting the syringe pipette. The plunger of the pipette fitted tightly in the barrel and was perfectly sealed by the oil against leakage of air. At reduced pressure, the plunger was held out against atmospheric pressure by hand until the air separated from the oil, a process requiring only about 1 minute.

The reduced-pressure experiments were run by operating in cycles, aerating at atmospheric pressure, and rapidly evacuating the system to observe whether temporary increases in amount of foam, total volume in the tank, or emulsified air in the oil were significantly great.

Experimental Results

The results of the aeration measurements are summarized in tables I to V. The measurements of the quantity of emulsified air reported in tables I to III were made by pouring or drawing the air-oil mixture into a graduated cylinder. The measurements of emulsified air in tables IV and V, however, were made by withdrawing a sample of the turbulent oil into a 30-cubic-centimeter syringe pipette. The syringe-pipette method more nearly measures the actual condition in the oil, since a large part of the air escapes by the time the sample is poured into a cylinder. The differences in quantity of air found by the several methods may be partially explained on this basis. The order of decreasing accuracy and of decreasing air content found would be:

(1) Syringe-pipette method (almost no air loss)

(2) Graduated-cylinder method with colloid mill (rate of efflux, extremely rapid; air loss, small)

(3) Graduated-cylinder method with electric kitchen mixer (pouring, slow; air loss, large)

(4) Graduated-cylinder method with gear-pump circulating system (fig. 4) (rate of efflux, slow; air loss, large)

The amount of air which could be emulsified in the oil by the beating method at 100° C was not enough to lighten the color of the oil very much. Not until the oil cooled to 55° C (table I) were large quantities of air in the oil.

Both foam enhancers (as in RPM Aviation) and foam inhibitors (such as Dow Corning Fluid or glycerol - Aerosol-OT mixture) tend to stabilize some dispersed air in the oil. The difference is that the foam enhancer stabilizes more air than would normally be in the unmodified oil, whereas the foam inhibitor facilitates the escape of most of the air but stabilizes

a fraction of what would be in the unmodified oil. This phenomenon appeared most markedly in the data from the beating method (table I) because the method of aeration measurement used did not detect the emulsified air which escaped in less than a minute. The annotations in table IV show that, although there was actually less air in the oil containing foam inhibitors, this amount of air showed less tendency to segregate than in the unmodified oil.

The colloid mill apparently cut the bubbles much finer than did the beating method. The gear pump, however, achieved the finest bubbles of all, especially when the system was operated at reduced pressures. Fine air bubbles originated in the bottom of the tank, streamed upward, and were easily visible against the sloping sides of the conical flask. As they rose toward the surface, they increased in size. The observations fit the explanation that air injected in the low-pressure side of the pump dissolves on the high-pressure side and comes out again in the low pressure of the flask. The difference in pressure between the high-pressure side of the pump and the tank increases as the pressure in the tank decreases, that is, the pressure in the pipe on the high-pressure side of the pump does not vary proportionately with the pressure in the tank.

The results of aeration of Aeroshell 120 at 100° C in the gear-pump circulating system at atmospheric pressure are given in table III. The rate of air injection does not affect measured air content of oil or foam height in the reservoir. The increased rate merely increases tank turbulence. Evacuation caused a slight reduction in the head of foam in the reservoir, the bubbles were smaller, and the foam was finer. Increasing the time of operation (run 6) did not change the aeration of the oil. The amount of air after 1-minute standing was less than 1 percent and the appearance did not vary with the treatment time. The arrangement used to obtain the data in table III is shown in figure 4. The oil return to the reservoir is immersed. The appearance without air injection and the head of foam (2 to 3 cm) formed when air is injected are shown in figures 4(a) and 4(b), respectively.

The measurements made on the effect of evacuation in the gear-pump circulating system are summarized in table V. The system was previously used with oil containing a high concentration of foam inhibitor. Despite the fact that at least a dozen different batches of oil and petroleum ether were subsequently circulated, there was still a progressive decrease in the foaming and aeration of a batch of oil for an hour or more. The oil was believed to be slightly less foaming in runs 1 to 5 (table V) than in runs 6 to 9 because of this contamination.

The aeration and appearance of the hot oil were observed during several cycles of evacuation and during return to atmospheric pressure with and without air injection. While circulating without air injection at atmospheric pressure, the oil was smooth flowing and dark; a copious foam formed when the oil stream from the pump plunged straight down into the oil surface but was eliminated by the elbow, which delivered the oil stream horizontally against the flask walls above the oil surface. When the oil was circulating with air injection at a pressure of 55 centimeters

of mercury (run 4, table V), fine bubbles of very uniform size streamed up the walls of the flask, being exceedingly small at the bottom and growing regularly as they rose. At a given depth, the bubbles near the flask walls were practically of a single size. Horizontal delivery of the oil stream against the flask walls at atmospheric pressure produced the same effect (run 7, table V). With the oil sliding down the flask walls directly from the pump, the evolution of the dissolved air probably became visible; it was previously obscured by the turbulence of the oil stream from the plunging of the pump into the center of the flask.

The volume of oil plus air in the flask, measured by the level of the top of the oil, was a minimum with the oil circulating at atmospheric pressure with no air injection. Injection of air caused about 5-percent increase in this volume. Evacuation with air injection caused an additional 4-percent increase, the volume now being about 9 percent greater than the minimum. Evacuation without air injection caused an intermediate volume increase, which was about 7 percent greater than the minimum volume.

The effect of reduced pressure was principally upon the dissolved air, as could be seen from the appearance of the oil. There appeared to be a greater pressure differential on the two sides of the gear pump with the system evacuated; consequently, a larger volume of air was released from solution in the low pressure of the tank. The bubbles of emulsified air in the tank appeared to be considerably smaller at reduced pressure than at atmospheric pressure, as can be seen by the approximate diameters noted in runs 7 and 8 (table V), which were estimated by use of the ocular micrometer net of a cathetometer placed against the side of the flask. The upper limit of the bubble size remained about the same, but the number of very fine bubbles greatly increased with reduced pressure.

Various attempts were made to obtain "flash" effects by sudden evacuation. In the most drastic of these, the air injection was adjusted to maximum aerating efficiency at atmospheric pressure, so that the hot oil became very turbid with emulsified air. The air injection valve was then closed and the system evacuated to a pressure of 35 centimeters of mercury in 10 seconds. Under this treatment, the oil volume rose only slightly (about 2 to 4 percent), quickly returned to the same position as at atmospheric pressure, and remained there. The oil-air volume with air injection at atmospheric pressure is about the same as without air injection at a pressure of 35 centimeters of mercury. This was the greatest flash effect obtained.

The air-emulsifying effect of a jet of oil falling from a height of 4 to 6 inches on the oil surface is nearly as great as that of air injected into the low-pressure side of the circulating gear pump or injected into the rotor of the colloid mill. The effect is indicated in table II and strikingly shown in the experiments with Aeroshell 120 alone in table IV. A jet of oil falling from a height of 1/2 inch emulsifies about twice as much air as an immersed delivery but only half

as much as a jet of oil falling from a height of 4 to 6 inches (Aeroshell 120 alone, table IV, compared with run 1, table V). Turning the jet horizontally, so that the entering oil streams down the walls of the tank, appears to have about the same effect in emulsifying air as the jet falling about 1/2 inch to the surface but has the advantage of producing a smaller head of foam. A horizontal inlet pipe, or fish tail, just below the oil surface would appear to offer advantages in permitting the air to escape without being further emulsified in the oil. The flask used for a tank in these experiments has a surface too small for testing this idea properly.

The appearance of the oil in the reservoir of the gear-pump circulating system, under aerating conditions, was the most convincing proof of the existence of air emulsions in oil. Under the violently turbulent conditions in the reservoir of the circulating system, the oil contained few large bubbles at a distance of a few centimeters from the inlet pipe. The oil, however, was full of small bubbles, which made the oil opaque and light in color. The oil quickly assumed this appearance after the pump was started and maintained it unchanged during the time of operation under aerating conditions. When the pump was stopped, the emulsified air quickly rose, formed a froth, and in about 1 minute was completely out of the oil.

Discussion

From the demonstrations with mechanical aerating systems the following results were obtained:

(1) Formation of an air emulsion is a visible and real phenomenon occurring in aerated oil. The term "emulsion" is used because the air is divided into numerous small bubbles, the most obvious analogy being to water-in-oil emulsions. The stability time of such air emulsions in unmodified aeronautical lubricating oils is of the order of 1/2 minute. The air in an air emulsion in oil may be 10 to 15 percent of the oil volume.

(2) The total amount of aeration in a system circulated by a gear pump is greater as the system is evacuated, as shown by the over-all increase in the volume of air plus oil in the system. The emulsified air, however, is not appreciably changed in quantity, but the size of the emulsified-air bubbles is reduced by evacuation. The increased aeration must therefore be due to entrained bubbles and slugs of air. The maximum increase in volume which could be caused by evacuation is estimated to be about 20 percent.

(3) Very rapid rates of evacuation do not cause appreciable flash effects, which result in large temporary increases in volume. The largest temporary volume increase obtained was 2 to 4 percent.

(4) Lubricating additives in the oil may increase the amount of air in an air emulsion and may stabilize it.

(5) The two foam-inhibiting additives, Dow Corning Fluid Type 200 and glycerol - Aerosol-OT mixture, even in the presence of lubricating additives, decrease the amount of emulsified air to from one-fifth to one-half of the volume it has in their absence but stabilize a large part of the residual air.

The term "air emulsion" can be defined strictly only in terms of bubble size, or, more accurately, in terms of bubble-size distribution. At present this description cannot be given quantitatively but a qualitative estimate would place the upper limit of size of emulsified-air bubbles in hot oil at a diameter of 1 millimeter. Most of the bubbles responsible for the opaque, yellow appearance of the air emulsion are obviously much smaller than 1 millimeter. The lightness of color of the emulsion is a rough gage of the fineness of subdivision and the quantity of the air; the finer the dispersion, the more effectively a given quantity of air lightens the color.

Nonemulsified air, that is, air in bubbles with a diameter larger than approximately 1 millimeter, escapes in a few seconds or a fraction of a second from oil at 100° C. The distinction between total amount of aeration and emulsified air has a practical significance, which may not have been appreciated before. For example, in studies on aircraft-engine oil tanks, tank efficiency is sometimes expressed as the ratio of aeration of outgoing oil to the aeration of oil entering the tank. It has been found elsewhere that, although tank efficiency varied tremendously with the aeration of the incoming oil, aeration of the outgoing oil varied only a few percent. If this statement is interpreted in terms of the experiments reported herein, the emulsified air was hardly affected by the total aeration and apparently went right through the tank. Since air other than emulsified air appears to be segregated easily from the oil, another informative value might be the ratio of emulsified air in the outgoing and the incoming oil.

The role of dissolved air in the problem of the aeration of aircraft lubricating oils has become more important. The dissolved air apparently is the principal factor involved in increasing the volume of the air plus oil in a gear-pump circulating system as the system is evacuated. The air is dissolved on the high-pressure side of the gear pump, which corresponds to the scavenging pumps of the airplane engine. The rate of solution of air under the conditions in the pump and pipes is very rapid. Since the air is furnished in great excess by the scavenging pumps, the oil is probably nearly saturated with air. As the pressure becomes less in the line leading to the tank and in the tank itself, the dissolved air comes out of the oil. Since air is dissolved in all parts of the circulating oil and comes out in bubbles which are extremely small but grow as the pressure on the oil decreases, an increase is inevitable in the volume of oil plus air between the scavenging pumps and the top of the tank as altitude is increased. Rapid separation of the air coming out of solution would tend to minimize this volume increase.

Gasoline in the oil would be expected to increase the volume of gas emerging on the low-pressure side of the cycle. At high concentration of gasoline, the volume of vapor might displace large volumes of oil from the engine.

In the comparatively small gear-pump circulating system used in these experiments, no significant flash effects could be obtained by rapid evacuation. This lack of flash effects may be due to the very high rate of flow of oil as compared with the volume of the oil, so that the aeration reaches a steady state in a very few seconds. The longer the time required for the oil to reach the tank where the air can escape, the greater will be the temporary increases of volume caused by sudden reduction of atmospheric pressure.

Some explanation of the effect of foam-inhibiting agents in facilitating the escape of most of the air and retarding the escape of the rest of the air is furnished by observations of the effect of Dow Corning Fluid Type 200 on the behavior of air bubbles injected from a pipette below the quiet surface of the oil. A coherent film of Dow Corning Fluid on the oil surface stabilizes bubbles against rupture. Dow Corning Fluid dispersed in the oil, however, promotes bubble coalescence below the surface and bubble rupture at the surface. It may therefore be reasoned that in the turbulent air-oil mixture in a rapidly circulating system most of the agent is effective in promoting bubble coalescence and escape of the air. However, a certain number of bubbles, by statistical chance, pick up enough Dow Corning Fluid to form coherent films on their inner surfaces and are much more resistant to coalescence and rupture than equal-sized bubbles in unmodified oil.

Dow Corning Fluid Type 200 and glycerol – Aerosol-OT mixture are both effective in counteracting the foam and emulsion stabilizing effect of the lubricating additives in RPM Aviation oil. However, the possibility that other lubricating additives might not be so effectively overcome cannot be ignored. It is considered that a liquid, oil-insoluble, foam and aeration inhibitor, of which the two lubricating additives described herein are representative, operates by virtue of its low surface tension, as compared with the surface tension of the oil. A lubricating additive could so lower the surface tension of the oil, or even raise the surface tension of the foam inhibitor, that the foam inhibitor would no longer be effective. Such an effect was observed in the case of an oil, the surface tension of which was greatly lowered by an extremely severe engine test; the agent which had completely defoamed the new oil was ineffective on the used oil, even when it was freshly added.

CONCLUDING REMARKS

1. Emulsified air is defined as the air dispersed in oil which will not rise to the free surface while the oil is being violently agitated

and continuously aerated and circulated. The amount of emulsified air depends on the mechanical arrangements and on the character of the oil. The quantity of emulsified air reaches its steady-state value in a few minutes of operation and does not change over a period of at least 2 hours if mechanical conditions remain constant.

2. The effect of reduced pressure on the tank of a gear-pump-oil-circulating system is to increase the total amount of aeration of the oil in the system. Emulsified air is more finely divided under reduced pressure.

3. Very rapid rates of evacuation of the tank of such a system cause small temporary increases in the total amount of aeration, which quickly subsides to the steady-state aeration for the new conditions.

4. The dissolved air is that part of the total amount of aeration which is primarily responsible for the increase in aeration at reduced tank pressure. The high pressure in the pump saturates the oil with air and the amount that comes out in the tank depends on the pressure in the tank. The highest pressure in the pump is relatively unaffected by reduced pressure in the tank.

5. No unmodified lubricating oil, 120 grade, could be made to contain more than 12 percent by volume of emulsified air at 100° C by any of the mechanical aerating methods tested.

6. An oil containing lubricating additives which greatly enhanced its frothing contained up to 15 percent emulsified air.

7. The foam-inhibiting additives that were tested reduced the emulsified air to about 2 to 4 percent when used in optimum concentration in either modified or unmodified oil and practically eliminated foam.

8. The two foam-inhibiting additives tested always reduced the amount of emulsified air. As the concentration of foam-inhibiting additive is increased, the amount of emulsified air decreases, but the stability of this reduced amount of air increases.

9. Of the two foam-inhibiting additives tested, Dow Corning Fluid Type 200 is effective at a lower concentration in reducing emulsified air but has a greater tendency to stabilize the emulsified air than the glycerol - Aerosol-OT mixture.

10. The rate of escape of emulsified air from an unmodified oil is so rapid at 100° C that 80 percent of it leaves the oil in about 30 seconds and all escapes in 1 minute.

Stanford University
Stanford Univ., Calif., June 13, 1945

REFERENCE

1. McBain, J. W., Ross, Sydney, and Brady, A. P.: Analysis of Properties of Foam. NACA TN No. 1840, 1949.

TABLE I

AERATION OF OILS IN ELECTRIC MIXER

Aeration of modified oils at 100° C			
Oil	Emulsified air (percent by volume) (a)	Time for clear oil surface to appear (min)	Remarks
Aeroshell 120	2 – 4	1	Foam segregates rapidly; oil clear in 1 min; no residual turbidity
RPM Aviation 120	2 – 3	>5	Segregated foam very stable; oil turbid (<1 percent air); slightly turbid after 30 min
Aeroshell 120 plus 0.1 percent Dow Corning Fluid Type 200	2	<2	Oil turbid (<1 percent air) for more than 6 min
Aeroshell 120 plus 0.67 percent glycerol plus 0.033 percent Aerosol OT	8 – 10	<3	Oil turbid; about 1 percent finely emulsified air; some turbidity persists after 7 min

Effect of temperature on aeration of Aeroshell 120[b]			
Oil	Temperature (°C)	Emulsified air (percent by volume)	Remarks
Aeroshell 120	100 55 45 35 25	[a]2 – 4 [c]15 [c]25 – 30 [c]35 – 40 [a]51	Appearance of oil changes sharply as temperature falls below 55° C; oil becomes more turbid, lighter in color, more opaque

[a]Measured by pouring oil-air mixture into graduated cylinder.
[b]Oil allowed to cool while being continuously beaten.
[c]Estimated visually from appearance of oil in mixing bowl.

TABLE II

AERATION OF AEROSHELL 120 AT 100° C IN COLLOID MILL

Run	Recycle (a)	Air injected (cc/min)	Emulsified air (percent by volume) (b)	Time for clear oil surface to appear (min)	Remarks
1	Baffled	None	2	<1	Oil still turbid after 6 min with 1 percent air
2	---do.---	24	5	<2	Do.
3	---do.---	88	5	<2	Do.
4	Unbaffled	88	8	<2	Do. (foam head in hopper increased)
5	---do.---	390	10	<2	Oil still turbid after 6 min with 1 percent air

[a]Recycle baffled by inserting sloping surface under jet and deflecting stream smoothly against side of hopper.
[b]Measured by drawing oil-air mixture from colloid-mill draincock into graduated cylinder. Rate of efflux, extremely rapid.

TABLE III

AERATION OF AEROSHELL 120 AT 100° C IN GEAR-PUMP

CIRCULATING SYSTEM AT ATMOSPHERIC PRESSURE

Run	Pump speed (rpm)	Air injection	Oil return to reservoir	Foam head in reservoir (cm)	Emulsified air (percent by volume) (a)	Remarks
1	575	Not used	Impingent	0.2	1	Atmospheric pressure, beaker reservoir
2	575	Used	---do.---	.2	2	Do.
3	575	---do.--	Immersed	0	2	Do.
4	2300	Not used	---do.---	0	2	Do.
5	2300	---do.--	Impingent	.5 – 1	2	Do.
6	2300	Used	Immersed	2 – 2.5	5 – 10	Do. (very finely divided air, rising rapidly)
7	2300	---do.--	---do.---	2	Turbid oil	Filter flask reservoir; atmospheric pressure
8	2300	---do.--	---do.---	1.5		Filter flask reservoir; pressure, 22 cm Hg

[a]Measured by drawing oil-air mixture from draincock of circulating system into graduated cylinder. Rate of efflux, slow.

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TABLE IV

AERATION OF MODIFIED OILS AT 100° C IN GEAR-PUMP

CIRCULATING SYSTEM AT ATMOSPHERIC PRESSURE

[Pump speed, 2300 rpm]

Oil	Air injection	Oil return to reservoir	Foam head in reservoir (cm)	Emulsified air (percent by volume) (a)	Remarks
Aeroshell 120	Not used ---do.-- Used ---do.--	Immersed Impingent Immersed Impingent	Trace 2 2 2.5 – 3	2,3,3,3 8,10,8 10,10,10 10,12,10	Coarse foam and emulsion; rapid air segregation
Aeroshell 120 plus 0.002 percent Dow Corning Fluid Type 200	---do.--	Impingent	0	4,8,6	Extremely fine stable emulsion
Aeroshell 120 plus 0.01 percent Dow Corning Fluid Type 200	Not used ---do.-- Used ---do.--	Immersed Impingent Immersed Impingent	0 Trace Trace Trace	0 Trace 4,4 5,3	A few scattered tiny bubbles; air would not segregate from oil
Aeroshell 120 plus 0.0022 percent glycerol plus 0.0007 percent Aerosol OT	Used	Immersed	Trace	8,10,8	After 5-min operation, oil was like Aeroshell alone
Aeroshell 120 plus 0.01 percent glycerol plus 0.0033 percent Aerosol OT	Not used ---do.-- Used ---do.--	Immersed Impingent Immersed Impingent	0 Trace 0 0	1.7,1.7,1.7 5,5,5 5,5,5 7,7,7	After 30-min operation, oil was like Aeroshell alone; extremely fine emulsion; segregates in 2 to 3 min
Aeroshell 120 plus 0.15 percent glycerol plus 0.05 percent Aerosol OT	Used ---do.-- ---do.--	Impingent ---do.--- ---do.---	0 0 0	1.2,3.2,2.3 2.0,1.6 No change in appearance	Segregates in 10 min Segregates in 1 hr Segregates in $3\frac{1}{2}$ hr
RPM Aviation 120 Sample No. 662.4 Received Sept. 1944	Not used Used Not used Used	Immersed ---do.--- Impingent ---do.---	Trace 2.5,3,3 2 2.5	2,3,3 10,10,10 16,10,13,13 [b]10,11	Half of air segregated in 1 min; trace of air left after 2 min (turbid oil) Half of air not segregated in 2 min
RPM Aviation 120 plus 0.01 percent Dow Corning Fluid Type 200	---do.--	---do.---	Trace	[b]2.4,3.9	Very stable air emulsion
RPM Aviation 120 plus 0.04 percent Dow Corning Fluid Type 200	---do.--	---do.---	Trace	[b]3.9,4.4	Very stable air emulsion

[a]Emulsified air determined by withdrawing air-oil sample in 30-cc syringe pipette from turbulent reservoir and by reading oil volume after air was segregated.
[b]Air would not segregate from oil in a reasonable time, so oil in syringe sample was weighed.

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TABLE V

EFFECT OF EVACUATION ON AERATION OF AEROSHELL 120 AT 100° C IN GEAR-PUMP

CIRCULATING SYSTEM

Run	Delivery into flask	Air injection	Pressure (cm Hg)	Emulsified air (percent by volume)	Foam (cm)	Remarks
1	Vertical	Not used	76	4 – 5	$\frac{1}{2}$ – 1	Foam on half of surface; oil dark; oil volume in flask, 1340 cc, 8 cm above bottom
2	Vertical	Used	76	7 – 8	$\frac{1}{2}$ – 1	Foam on whole surface; oil light; oil volume in flask, 1400 cc, 9 cm above bottom
3	Vertical	Used	27	7		Oil level in flask 9.7 cm above bottom returning to 9 cm in 2 min
4	Vertical	Used	55	7 – 8	$\frac{1}{2}$ – 2	Foam on whole surface; oil volume in flask, 1460 cc, including foam, 1570 cc; oil light; fine bubbles streaming up flask walls
5	Vertical	Not used (except leakage)	55	6 – 7	0 – 1	Foam on most of surface; oil dark; no pronounced streaming of bubbles up flask walls; oil volume in flask, 1430 cc
6	Horizontal	Not used	76	4	None	Oil dark; oil volume in flask, 1340 cc
7	Horizontal	Used	76	8	1	Bubbles streaming up sides of flask; diam. at top, 0.3 to 0.6 mm; diam. at bottom, 0.02 to 0.2 mm; average diam., about 0.1 mm
8	Horizontal	Used	35	10	$1\frac{1}{2}$	Foam on whole surface; fine bubbles streaming up flask; diam. at top, 0.4 mm; diam. at bottom, 0.1 to 0.2 mm
9	Horizontal	Not used (except leakage)	35	11 – 12		Oil volume in flask, 1460 cc

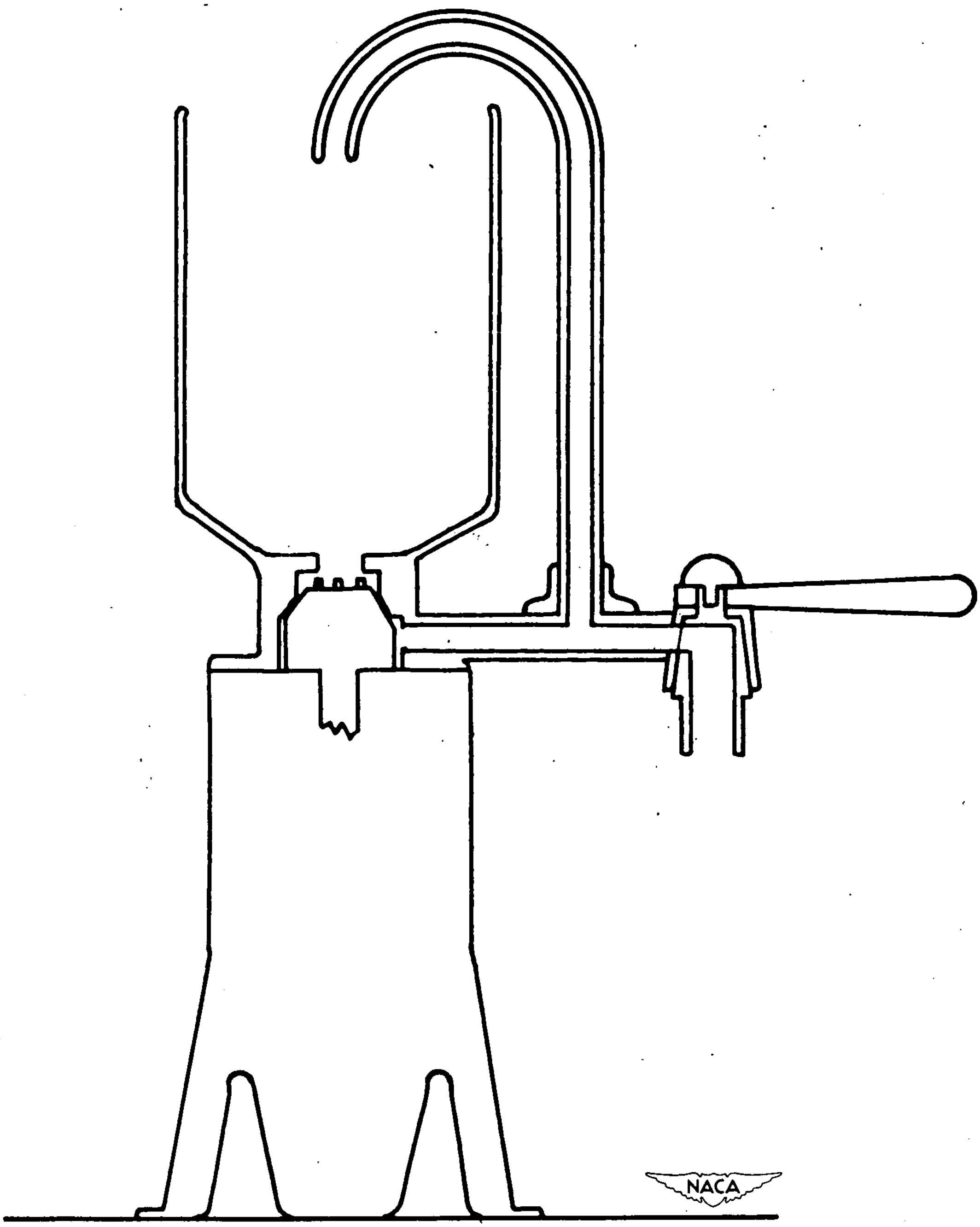

Figure 1.- Schematic diagram of colloid mill.

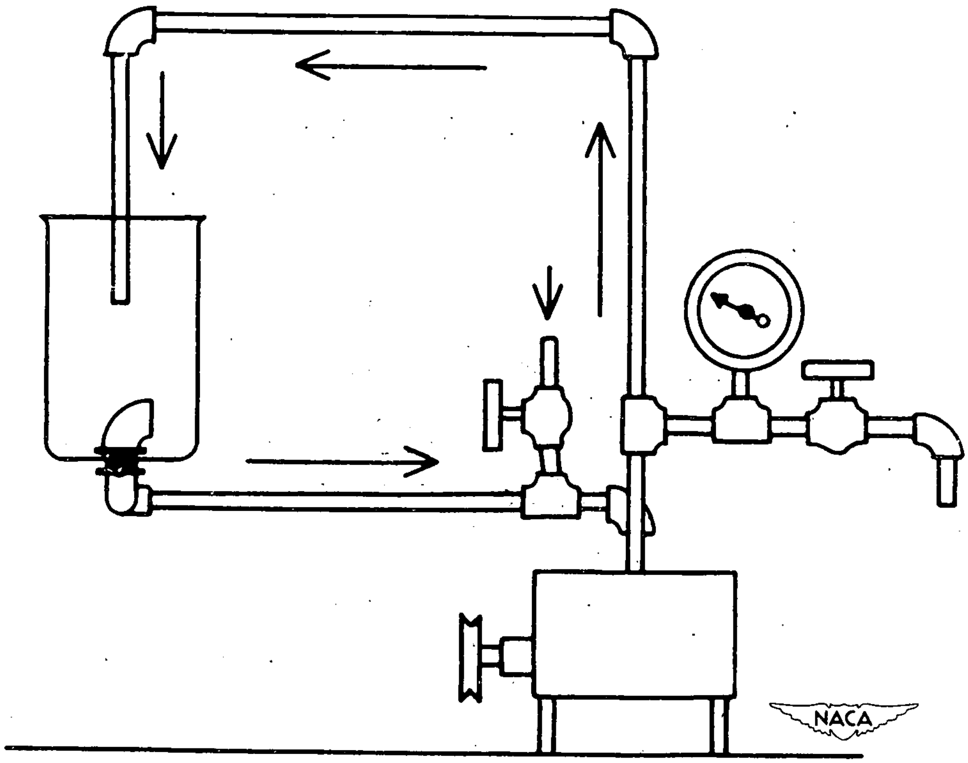

Figure 2.- Gear-pump circulating system for operation at atmospheric pressure.

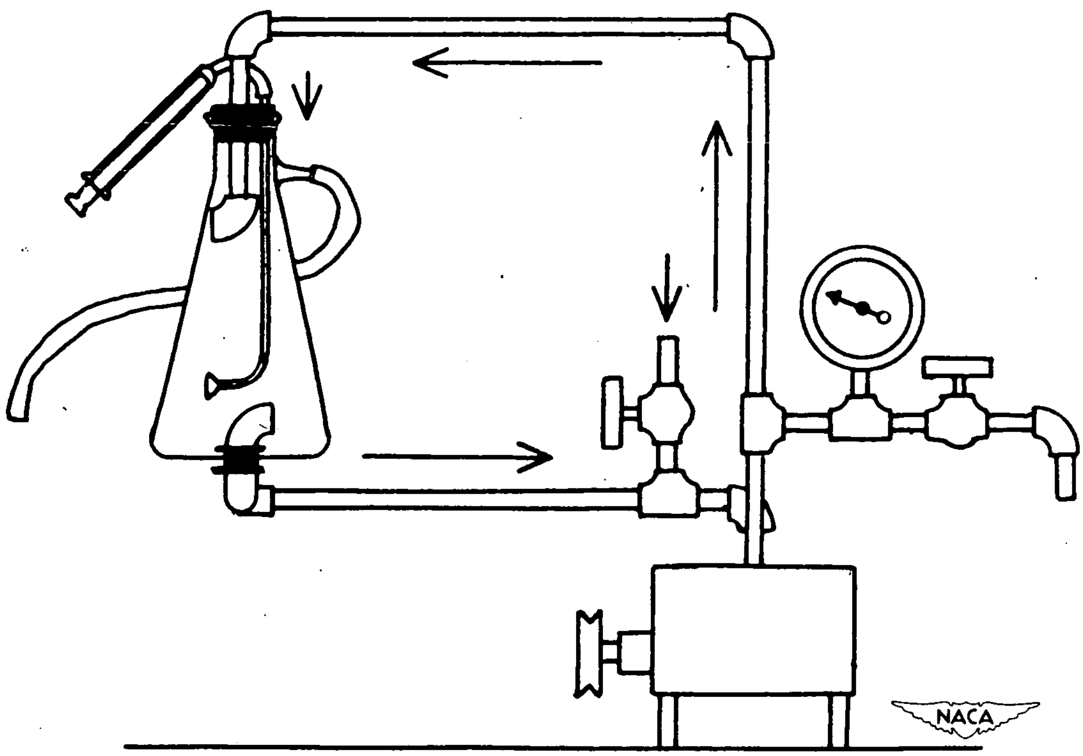

Figure 3.- Gear-pump circulating system for operation at reduced pressure.

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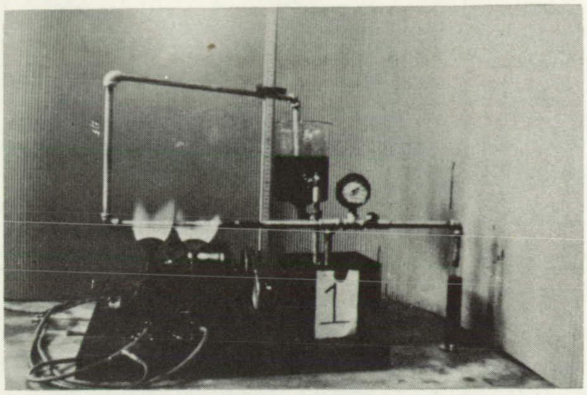
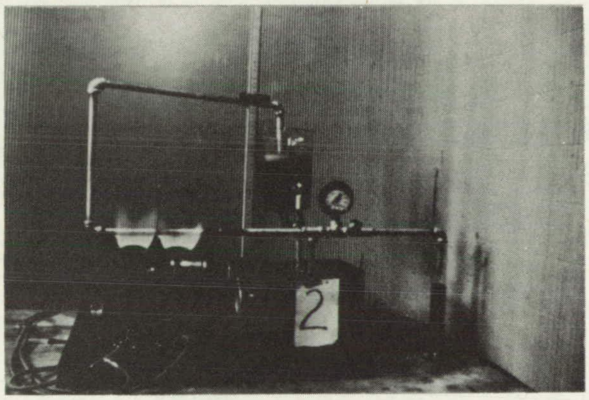


(a) Without air injection.



(b) With air injection.

Figure 4.- Gear-pump circulating system.